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C++ Error Handling

Exceptions, std::expected and Modern Alternatives

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Author's Introduction

Error handling is one of the most defining characteristics of a programming language. It influences correctness, performance, readability, maintainability, and the robustness of entire software systems. In C++, the evolution of error-handling mechanisms has been long and complex—shaped by decades of real-world experience and millions of lines of industrial-grade code.

In this booklet, **C++ Error Handling — Exceptions, `std::expected`, and Modern Alternatives**, we explore both the classic and the modern approaches to error management, focusing on how C++ developers can design safer, more efficient, and more readable systems in 2025 and beyond.

This booklet introduces:

- Traditional exception handling and its zero-cost model.
- Performance implications and ABI details.
- Error codes and return-type-based approaches.
- The introduction of `std::expected<T, E>` in C++23 and its major impact on modern design.
- Monadic operations and functional error propagation.
- New C++26–C++29 proposals shaping the future of error handling.

- Practical guidelines that every professional C++ developer should follow.

Every chapter includes carefully designed exercises and complete solutions, ensuring that this booklet serves as both a learning resource and a reference for future projects.

Chapter 1

Foundations of Error Handling in C++

1.1 Why Error Handling Matters

Error handling determines how a program detects, reports, and recovers from unexpected conditions. In C++, error handling is tightly connected to:

- performance constraints,
- low-level system programming,
- exception safety guarantees,
- resource management (RAII),
- and generic programming.

1.2 Three Major Families of Error Handling in C++

C++ supports multiple paradigms:

1. **Return-value error codes** (C-style)
2. **Exceptions** (introduced in C++98)
3. **Value-based error types** (e.g., `std::optional`, `std::variant`, and `std::expected`)

The choice among them depends on performance goals, API design philosophy, and the intended error semantics.

1.3 Error Taxonomy

Errors fall into categories:

- **Recoverable errors**: e.g., failed network calls.
- **Unrecoverable errors**: e.g., logic violations, invalid memory.
- **Domain errors**: calling a function outside its valid conditions.
- **IO/OS errors**: files, sockets, syscalls.

Understanding these categories enables developers to choose the appropriate handling mechanism.

1.3.1 Example: Traditional Error Codes

```
int read_file(const std::string& path, std::string& out) {
    FILE* f = fopen(path.c_str(), "r");
    if (!f) return -1;

    char buffer[256];
```

```
    while (fgets(buffer, sizeof(buffer), f)) {
        out += buffer;
    }
    fclose(f);
    return 0;
}
```

This approach is explicit but leads to verbose, error-prone code.

1.3.2 Example: Exception-Based

```
std::string read_file(const std::string& path) {
    std::ifstream file(path);
    if (!file)
        throw std::runtime_error("Cannot open file");

    return { std::istreambuf_iterator<char>(file),
             std::istreambuf_iterator<char>() };
}
```

Shorter, but potentially costly in performance-critical contexts.

Exercises — Chapter 1

1. Rewrite the error-code example using `std::optional<std::string>`.
2. Identify three domains in your personal projects where exceptions are not appropriate.
3. Explain why exception safety guarantees are important for RAII.

Solutions — Chapter 1

1. ```cpp
   std::optional<std::string> read_file_opt(const std::string& path) {
       std::ifstream f(path);
       if (!f) return std::nullopt;
       return std::string(std::istreambuf_iterator<char>(f),
                          std::istreambuf_iterator<char>());
   }
   ```

2. Common examples include: (1) hard real-time audio engines, (2) kernel-mode drivers, (3) embedded microcontrollers with no unwinding support.

3. RAII requires deterministic destruction. Exceptions trigger stack unwinding; without strong exception safety, resources can leak or become corrupted.
   ```

Chapter 2

The C++ Exception Model

2.1 Zero-Cost Exceptions

C++ exceptions are designed around the **zero-cost model**: *throwing is expensive, normal execution is not*.
Compilers generate two paths:

- the normal, fast execution path,
- metadata tables for unwinding during exceptional cases.

This design differs from Java, C#, and Python, where exceptions impose runtime overhead even when unused.

2.2 Stack Unwinding

When an exception is thrown:

1. the runtime locates a matching handler,

2. destructors run in reverse order (RAII),

3. the program resumes at the catch block.

2.3 `noexcept` and Its Semantics

`noexcept` communicates intent and enables optimizations:

```
void f() noexcept;  // cannot throw
```

If a `noexcept` function throws, the program calls `std::terminate()`.

2.4 Performance Considerations

Exceptions are powerful but problematic when:

- branching is frequent,
- error rates are high,
- stack unwinding is too costly.

This is why real-time engines and embedded systems often disable exceptions entirely.

2.4.1 Example: Exception Safety Levels

- **No guarantee**: program may leak resources.
- **Basic guarantee**: object remains in valid state.
- **Strong guarantee**: operation rolled back on failure.
- **No-throw guarantee**: guaranteed no exceptions.

Exercises — Chapter 2

1. Write a small class that provides the strong exception guarantee for push-back into a dynamic buffer.

2. Explain the difference between `noexcept` and `throw()`.

3. Describe a situation where exceptions cannot be used at all.

Solutions — Chapter 2

1. ```
   class Buffer {
       std::vector<int> data;
   public:
       void push_back_strong(int x) {
           std::vector<int> tmp = data; // copy
           tmp.push_back(x);            // may throw
           data.swap(tmp);              // commit
       }
   };
   ```

2. `throw()` (deprecated) meant no exceptions could be thrown. `noexcept` is compile-time checked and enables optimizations.

3. In kernel-mode drivers (e.g., Linux kernel modules), exceptions cannot be used due to ABI restrictions and unwinding unavailability.
   ```

Chapter 3

Error Codes, Status Types, and Modern Alternatives

3.1 Introduction

Before exceptions and before value-based error types (such as `std::optional` and `std::expected`), the primary method of error reporting was the return-value error code. Although often considered old-fashioned, error codes remain widely used—especially in performance-critical and embedded systems where throwing exceptions is not acceptable. Modern C++ has expanded this approach by introducing type-safe wrappers, monadic transformations, and structured error types that make error handling explicit and more readable.

3.2 Classic Error Codes

Legacy C APIs use integer error codes:

```
int write_to_socket(int fd, const void* buf, size_t size);
```

Problems include:

- no type safety,
- ambiguous meanings,
- error handling boilerplate,
- no enforced convention.

3.3 Status Enums and Strong Types

Modern code improves error codes using `enum class`:

```
enum class FileStatus {
    Ok,
    NotFound,
    PermissionDenied,
    IOError
};

FileStatus load_config(const std::string& path) {
    std::ifstream in(path);
    if (!in) return FileStatus::NotFound;
    // ...
    return FileStatus::Ok;
}
```

This provides clarity, type safety, and documented error semantics.

3.4 Return-Value Structs

Another modern idiom is returning structured results:

```
struct LoadResult {
    bool ok;
    std::string content;
    std::string error_message;
};
```

Simple and expressive, but requires careful support code.

3.5 `std::optional` and Its Limits

`std::optional<T>` expresses “T or nothing”:

```
std::optional<User> find_user(int id);
```

However, it lacks:

- error messages,
- rich diagnostic details,
- alternative error categories.

This paved the way for **std::expected**.

3.6 Error Handling via `std::variant`

`std::variant<T, E>` can model either success or error, but:

- requires manual checking,

- lacks standard monadic helpers,
- does not communicate intent clearly.

Thus, C++23 standardized a dedicated type.

3.6.1 Example: A Small Status Type

```
struct Status {
    bool ok;
    std::string message;

    static Status Ok() { return {true, ""}; }
    static Status Error(std::string m) { return {false, m}; }
};
```

While usable, this re-invents what `std::expected` already provides more elegantly.

Exercises — Chapter 3

1. Implement a strong-typed error enum for a file parser.
2. Rewrite a function returning `int` error codes into a function returning a structured `Result<T>`.
3. Identify two limitations of `std::optional` as an error type.

Solutions — Chapter 3

1. ```
   enum class ParseError {
       Ok,
       InvalidToken,
       UnexpectedEnd,
       MissingField
   };
   ```

2. ```
   template <typename T>
   struct Result {
       bool ok;
       T value;
       std::string error;
   };

   Result<int> compute(int x) {
       if (x < 0) return {false, 0, "Negative value"};
       return {true, x*2, ""};
   }
   ```

3. `std::optional` cannot store error messages or error categories and makes debugging harder since it conveys only “present or not.”

Chapter 4

`std::expected` in C++23 — Design, Usage, and Monadic Operations

4.1 Why `std::expected`?

For years, the C++ community sought a standardized alternative to exceptions for expressing recoverable errors without the complexity and cost of unwinding.
Key motivations:

- more readable APIs,
- explicit control flow,
- lightweight error propagation,
- alignment with functional programming techniques,
- safer alternatives to raw error codes.

4.2 Basic Structure

`std::expected<T, E>` represents:

$$\text{either a value } T \quad \text{or an error } E$$

```
std::expected<int, std::string> parse_int(const std::string& s);
```

4.3 Creating Values and Errors

```
return 42;                          // value
return std::unexpected("error"); // error
```

4.4 Checking State

```
auto r = parse_int("123");

if (r) {
    std::cout << *r;       // success
} else {
    std::cout << r.error();  // error
}
```

4.5 Monadic Operations

C++23 introduces powerful monadic tools:

- **map** Transform success: `map(f)` applies `f` to the stored value.
- **and_then** Chain computations that may also fail.
- **or_else** Transform or recover from error.

4.5.1 Example: map

```
auto r = parse_int("10").map([](int x){ return x * 2; });
```

4.5.2 Example: and_then

```
std::expected<double, std::string>
compute(const std::string& s) {
    return parse_int(s)
        .and_then([](int x) -> std::expected<double, std::string> {
            if (x == 0) return std::unexpected("zero division");
            return 100.0 / x;
        });
}
```

4.5.3 Example: or_else

```
auto r = parse_int("xyz").or_else([](auto err) {
    return std::expected<int, std::string>{0};
});
```

4.6 Error Propagation Pattern

Using monadic chaining eliminates deeply nested `if`-statements.

4.6.1 Comparison to Exceptions

- **Exceptions**: implicit propagation, expensive when thrown.
- **Expected**: explicit flow, cheaper, composable.

4.7 Designing E Types

`E` (error type) can be:

- a string,
- an enum,
- a structured error type,
- small POD optimized for performance.

Example:

```
enum class ReadError { NotFound, Permission, IO };

using ReadResult = std::expected<std::string, ReadError>;
```

Exercises — Chapter 4

1. Implement a function that returns `std::expected<double, std::string>` to compute a square root with domain checking.
2. Rewrite a sequence of three dependent operations using `and_then`.
3. Create a custom error struct and use it as the `E` type in a small API.

Solutions — Chapter 4

1. ```
   std::expected<double, std::string> safe_sqrt(double x) {
       if (x < 0)
           return std::unexpected("negative input");
       return std::sqrt(x);
   }
   ```

2. ```
   auto r = op1()
       .and_then([](int a){ return op2(a); })
       .and_then([](int b){ return op3(b); });
   ```

3. ```
   struct FileError {
       enum Kind { NotFound, Permission, IO } kind;
       std::string detail;
   };

   std::expected<std::string, FileError> load_text(const std::string& p);
   ```
   ```

Chapter 5

Error Handling in Templates and Generic Programming

5.1 Introduction

Generic programming in C++—based on templates, concepts, and compile-time constraints—creates unique challenges for error handling. Unlike runtime polymorphism, templates require mechanisms that support:

- static constraints checking,
- compile-time validation,
- flexible error propagation across multiple instantiations,
- compatibility with a wide range of types and APIs.

Error handling in template-heavy libraries (e.g., ranges, networking, filesystems, coroutines) must be expressive, composable, and compatible with strict compile-time guarantees.

5.2 SFINAE and Error Signaling Before Concepts

Before C++20, templates encoded errors through:

- SFINAE (Substitution Failure Is Not An Error),
- `enable_if`,
- tag dispatching.

These patterns were often cryptic:

```
template <typename T>
std::enable_if_t<std::is_integral_v<T>, bool>
is_valid(T x) { return x > 0; }
```

This approach encodes error conditions (invalid use) at compile time.

5.3 Concepts and Improved Error Diagnostics

C++20 concepts dramatically improved template error clarity:

```
template <typename T>
requires std::integral<T>
bool is_valid(T x) { return x > 0; }
```

Now, misuse of the API triggers clear compile-time diagnostics rather than template instantiation failures.

5.4 Error Types in Generic Code

Templates often return polymorphic error types.
Example:

```
template <typename Parser, typename T>
std::expected<T, typename Parser::error_type>
parse_with(Parser p, std::string_view data) {
    return p.parse(data);
}
```

The template returns an *expected* where the error type depends on the parser implementation.

5.5 Customizing Error Propagation

Generic pipelines require custom propagation:

```
template <typename F, typename T, typename E>
auto transform_expected(std::expected<T, E> ex, F f) {
    if (ex) return std::expected{ f(*ex) };
    return std::unexpected(ex.error());
}
```

Generic error propagation code forms the basis of composable libraries.

5.6 Constraints on Error Types

Error types must often satisfy:

- copyability or moveability,
- small-size requirements,

- no dynamic allocation in embedded systems,
- interoperability across translation units.

5.7 Compile-Time Validation

Templates sometimes encode compile-time error conditions:

```
template <typename T>
constexpr std::expected<T, const char*> make(T value) {
    if (!std::is_trivially_copyable_v<T>)
        return std::unexpected("T must be trivially copyable");
    return value;
}
```

This hybrid form blends compile-time and runtime error checks.

Exercises — Chapter 5

1. Write a concept that ensures a type has a `size()` member function.
2. Create a template function returning `std::expected<T, std::string>` enforcing a compile-time restriction.
3. Explain why templates benefit more from `std::expected` than from exceptions.

Solutions — Chapter 5

1. ```cpp
   template <typename T>
   concept HasSize = requires(T x) {
       { x.size() } -> std::convertible_to<std::size_t>;
   };
   ```

2. ```cpp
   template <typename T>
   std::expected<T, std::string>
   checked_value(T v) {
       if (!std::is_default_constructible_v<T>)
           return std::unexpected("T must be default-constructible");
       return v;
   }
   ```

3. Templates benefit from explicit value-based error handling because exceptions hide error paths, while templates need deterministic, generic behavior that composes easily across many layers and instantiations.

Chapter 6

Error Handling in Concurrency and Coroutines

6.1 Introduction

Concurrency introduces new dimensions to error handling:

- thread boundaries,
- async return channels,
- cancellation and timeouts,
- synchronization hazards,
- race-condition diagnosis.

Coroutines, introduced formally in C++20, created new demand for structured, propagation-friendly error types.

6.2 Error Handling in Threads

Threads cannot propagate exceptions across boundaries automatically. Code like this is unsafe:

```
std::thread t([]() {
    throw std::runtime_error("error");
});
t.join();  // undefined behavior or std::terminate
```

Correct patterns:

- use `std::promise/std::future`,
- return `std::expected`,
- use thread-safe channels.

6.3 Using `std::future`

```
std::future<int> f = std::async([] {
    if (/* failure */) throw std::runtime_error("err");
    return 42;
});
```

When calling `f.get()`, the exception is rethrown.

6.4 Using `std::expected` in Threads

```
std::expected<int, std::string> result;
```

```
std::thread t([&] {
    try {
        result = 42;
    } catch (const std::exception& e) {
        result = std::unexpected(e.what());
    }
});

t.join();
```

A clear pattern, especially for embedded or async event loops.

6.5 Error Handling in Coroutines

Coroutines introduce new control flow:

- suspend,
- resume,
- cancel,
- propagate errors.

The coroutine promise type determines how errors propagate.

6.6 Custom Error Storage

Coroutines can store errors in the *promise*:

```
struct Task {
    struct promise_type {
```

```
        std::string error;
        void unhandled_exception() {
            error = "Exception in coroutine";
        }
        Task get_return_object() { return {}; }
        std::suspend_always initial_suspend() { return {}; }
        std::suspend_always final_suspend() noexcept { return {}; }
        void return_void() {}
    };
};
```

6.7 Expected-Based Coroutine Results

C++23 encourages writing coroutine types that return:

`expected<T, E>`

Example:

```
expected<int, std::string> task();
```

This eliminates invisible error paths in asynchronous logic.

Exercises — Chapter 6

1. Why can't exceptions propagate naturally across threads?
2. Write a coroutine that returns `std::expected<int, std::string>`.
3. Convert a failing threaded computation into an `expected`-returning pattern.

Solutions — Chapter 6

1. Because each thread has its own stack, and unwinding cannot cross stack boundaries—threads represent separate execution contexts.

2. ```
   #include <expected>
   #include <coroutine>

   Task<std::expected<int, std::string>> co_compute() {
       co_return 42;
   }
   ```

3. ```
   std::expected<int, std::string> result;

   std::thread t([&] {
       try {
           // work...
           result = 5;
       } catch (const std::exception& e) {
           result = std::unexpected(e.what());
       }
   });
   t.join();
   ```

Chapter 7

Modern Guidelines and Best Practices

7.1 When to Use Exceptions

Use exceptions when:

- errors are rare,
- control flow should remain clean,
- strong exception guarantees are needed,
- performance is acceptable,
- RAII boundaries control resource cleanup.

7.2 When to Prefer `std::expected`

Use expected when:

- error frequency is high,

- low-latency paths require predictable flow,
- deeply chained computations need readable propagation,
- building parsers, interpreters, or functional pipelines,
- working in real-time or embedded systems where exceptions are banned.

7.3 When to Use `std::optional`

`optional` should represent:

- “value missing” conditions,
- “not found” results,
- simple, non-error absence states.

7.4 APIs Should Not Mix Paradigms

Mixing approaches causes confusion:

- exceptions + return error codes,
- expected + optional for errors,
- partial exception handling with partial monads.

Choose one strategy per subsystem.

7.5 Error Messages Should Not Be Raw Strings

Prefer structured error types:

```
struct ParseError {
    enum Kind { Token, EOFError, Invalid } kind;
    std::size_t position;
};
```

Structured errors encode meaning.

7.6 Prefer Small Error Types

Guideline:

$$\text{sizeof(E)} \leq 16 \text{ bytes}$$

Avoid large payloads, dynamic allocations, or expensive diagnostics in inner loops.

7.7 Document Your Error Model

Every subsystem needs a documented model:

- error categories,
- recovery rules,
- guarantees,
- propagation rules,
- thread interactions.

Clear documentation prevents misuse.

Exercises — Chapter 7

1. Provide an example where `optional` is strictly better than `expected`.

2. Write a structured error type for a JSON parser.

3. Design a simple API and choose the correct error model for it.

Solutions — Chapter 7

1. `optional` is better when absence is normal (e.g., find a key in a map). No need for error diagnostics or propagation.

2. ```
   struct JsonError {
       enum Kind { MissingBrace, InvalidToken, UnexpectedEOF } kind;
       std::size_t position;
       std::string token;
   };
   ```

3. Example: a configuration loader. `expected` is ideal because loading may fail with rich diagnostics.
   ```

Final Conclusion

Error handling has always been one of the most controversial and impactful aspects of C++ design. Its dual identity as both a high-level language and a systems language forces developers to balance safety, performance, clarity, and expressiveness.
This booklet explored the historical context, modern techniques, and future direction of error handling in C++—from traditional return-value patterns to exceptions, monadic transformations, and the introduction of `std::expected<T, E>` in C++23.

The Role of Exceptions Today

Exceptions remain powerful when used in the right context:

- They enable concise and clean APIs.
- They integrate naturally with RAII and unwinding.
- They offer strong semantic guarantees.

However, for systems where predictability and low latency are required, exceptions impose constraints that limit their use.

The Rise of Value-Based Error Handling

The adoption of `std::expected<T, E>` marks a cultural shift toward more explicit, functional, and optimized error models. It provides:

- clarity in APIs,
- predictable control flow,
- rich error information,
- excellent composability via monadic operations,
- seamless integration with templates and modern interfaces,
- safer alternatives for embedded, real-time, and large-scale systems.

With `expected`, C++ finally aligns with modern languages such as Rust, Swift, and Haskell while preserving its core strengths.

Error Handling in the Future of C++

Upcoming standards (C++26–C++29) continue to refine error-handling mechanisms through:

- contracts (assertion-based correctness),
- improved monadic utilities,
- coroutine integration patterns,
- more unified error-handling idioms across standard libraries.

C++ is evolving toward a consistent, expressive model that encourages safer and more maintainable codebases.

Final Thoughts

The decision of which error-handling model to adopt must always be based on:

- performance constraints,
- codebase scale,
- latency requirements,
- interaction with concurrency and templates,
- developer experience,
- clarity of API boundaries.

This booklet is meant to help modern C++ developers evaluate and choose the right technique for each subsystem. Whether you build embedded firmware, distributed services, compilers, kernels, or high-frequency trading systems, a deep understanding of error handling is foundational to producing correct, efficient, and maintainable software.

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